THE NEGATIVE IMPACT OF COLD WATER BYPASS ON SOLAR DOMESTIC HOT WATER SYSTEMS

Final Report

DRAFT

Prepared for

THE NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

Albany, NY

Robert M. Carver, P.E.

Project Manager

NEW YORK CITY ECONOMIC DEVELOPMENT CORPORATION

New York, NY

Harry Charalambides

Project Manager

Prepared by:

BRIGHT POWER, INC.

New York, NY

Skye Gruen, BPI-MFBA
Conor Laver, PhD
Andrew McNamara, C.E.M., LEED A.P.
Jeffrey Perlman, C.E.M., BPI-MFBA, LEED A.P.
Project Managers

NYSERDA Agreement No. 19712/
PO No. 21662

NYCEDC Agreement No. 42620001

NYSERDA
Report XX-XX

August 2011

NOTICE

ABSTRACT AND KEY WORDS

A solar domestic hot water (SDHW) system is designed to save fossil fuels or electricity by reducing the energy used by conventional domestic hot water (DHW) appliances. System efficiency is dependent upon the assumption that the vast majority of incoming cold water will be preheated by the SDHW and will not enter the DHW system in any other way[1]. When incoming water is diverted from the preheat tanks, thermal energy captured by the solar collectors is not distributed to the DHW system, and the conventional appliance has to provide more heat and consume more fuel.

This paper presents an analysis of the internal dynamics of the flow of thermal energy and hot water through a solar domestic hot water (SDHW) system installed in a multifamily high-rise apartment building in the Bronx. The purpose of this study was to: (1) determine why this specific SDHW system's thermal performance is demonstrably lower than predicted; (2) assess the effects of a recirculation pump and a mixing valve on the output of SDHW systems in general; (3) identify a potentially endemic problem in multifamily high-rise buildings that negatively impacts the performance of SDHW systems and other building systems that employ preheated water in their operation; and (4) identify diagnostic techniques and potential solutions to this problem.

Although the solar thermal system functions correctly and harnesses heat energy during the day by storing it in domestic hot water preheat tanks, it has been observed that the majority of this hot water does not get transferred to the building DHW system, resulting in sub-optimal performance of the SDHW system. Monitoring of system flows and temperatures demonstrate that such performance degradation is caused by **cold water bypass**; cold water enters the DHW system by means that circumvent the solar preheat tanks, reducing the net flow of water through these tanks and impeding the distribution of the stored solar thermal.

As defined, cold water bypass has two components; **mixing valve bypass**, which is intentional to the original design of the system, and **rogue bypass**, which is unintentional and derives from a source of cold water that is not readily identifiable.

Rogue bypass accounts for 82% of the water entering the DHW system – this means that the water drawn through the preheat tanks is reduced to 18% of what the system was designed for. This reduction of flow was found to result in a 45% average reduction in system performance during the measuring period. Mixing valve bypass alone has a negligible effect on system performance, and in the absence of rogue bypass is necessary for safe operation of the system. When combined, rogue bypass and mixing valve bypass represent an even greater percentage of the water

[1] A small portion of the entering cold water is typically designed to flow through a tempering or mixing valve for scald protection.

available to flow through the preheat tanks, and the net resulting system performance degradation increases along with the greater percentage of cold water bypass.

Future studies will investigate the hypothesis that this phenomenon is prevalent among other high-rise buildings and may have significant implications to the design and installation of SDHW systems, cogeneration systems, and other processes utilizing a preheat strategy.

Keywords: Solar, Thermal, Hot Water, New York, Bronx, Energy, SDHW, Crossover Flow, Rogue Bypass, Mixing Valve Bypass, Cold Water Bypass

ACKNOWLEDGEMENTS

The authors wish to thank several individuals whose substantial contributions enabled this research and analysis: David Bradley (Thermal Energy System Specialists) for support in the initial experimental set-up and in energy modeling and analysis using TRNSYS; Steven Valdez and J.W. Moore (GE Sensing) for technical support for instrumentation and monitoring equipment; Robert Carver (NYSERDA) and Harry Charalambides (NYCEDC) for thoughtful and constructive feedback throughout the process; Russ Horner (Water Management, Inc) for anecdotal evidence of DHW system underperformance in buildings with low-flow fixtures and recirculation pumps; Peter Magistro, Steven Baranello, Julio Saldana, Julio Arrendel and Freddy Rodriguez of BronxPro for their many hours of on-site support; and Dan Fink, Soomok Lee, Jeff Schwane, and Bishoy Takla of Bright Power for their significant contributions and collaboration in writing this report.

CONTENTS

FIGURES

TABLES

SUMMARY

A solar domestic hot water (SDHW) system is designed to preheat the domestic hot water for a building. It saves fossil fuels or electricity by reducing the runtime required of the conventional domestic hot water (DHW) appliance, because the conventional appliance is not required to supply as much heat. The proper functioning of the SDHW system is predicated on the fundamental assumption that the vast majority of cold mains water to be heated for DHW will flow through the SDHW system, and will not enter the conventional DHW appliance some other way[2].

Post-installation monitoring of a 24 collector SDHW system recently installed in the Bronx revealed that the overall performance of the system is far lower than expected. The initial hypothesis for the cause of this reduced performance posited that less water is being drawn through the preheat tank than designed for, thereby impeding the distribution of the thermal energy collected and reducing the efficiency of the solar thermal system. To investigate this theory, a study was commissioned to analyze the internal dynamics of the system through a joint effort between Bright Power, the New York State Energy Research and Development Authority (NYSERDA), the New York City Economic Development Corporation (NYCEDC).

Using a 10-point temperature and 2-point flow sensor setup[3] for six months, together with hourly energy simulations[4], Bright Power analyzed the thermal and fluid dynamics of the domestic hot water (DHW) system. We found that the primary cause of this problem is **cold water bypass**, whereby cold water makeup from the mains plumbing line is circumventing the solar preheat tank. The theoretical foundation for the effect of cold water bypass is shown in the figure below – as cold water bypass increases, the performance of the system decreases.

[2] A small portion of the entering cold water is typically designed to flow through a tempering or mixing valve for scald protection

[3] These sensors are in addition to the temperature and flow sensors installed prior to this study on the solar collector and heat transfer portion of the system.

[4] Hourly Energy Simulations were conducted in TRNSYS.

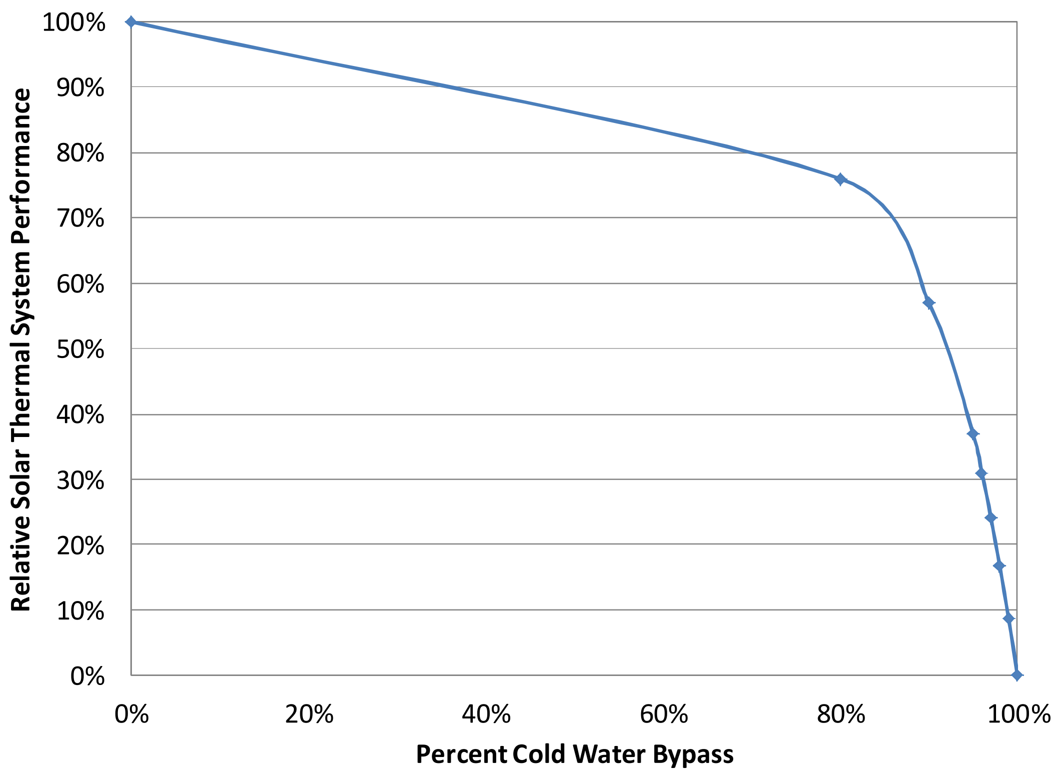

Figure S-1: The negative effect of cold water bypass on solar thermal system performance[5]

As defined, cold water bypass has two components: **mixing valve bypass** and **rogue bypass**. **Mixing valve bypass**, whereby cold water enters the DHW system at the cold side of the mixing valve rather than through the solar preheat tank, was intentional to the original design as a safety feature for summer months when the system is delivering higher temperature water than is safe for occupants. **Rogue bypass** is a phenomenon in which cold water bypasses a preheat system by entering the DHW system elsewhere in the building via a pathway that was not intended and is difficult to pinpoint. It was determined in this study that for this system the majority of the performance degradation is the result of rogue bypass. The negative impact of mixing valve bypass is a secondary effect that becomes significant only when rogue bypass is present. ***During the period of measurement, rogue bypass accounted for on average 82% of cold water entering the DHW system.***

When large amounts of cold water bypass the solar preheat tank, SDHW stored in the tank is prevented from circulating to the DHW system. This causes heat produced by the solar thermal system to build up in the preheat tank instead of being drawn out in response to occupant demand, so much so that the preheat tank temperatures

[5] Note: this chart is specifically prepared for this particular solar thermal system, which has a projected annual solar fraction (percent of DHW provided by the solar system) of 11-12%. This chart would be different for other systems with other solar fractions.

remain high even at 7:30 am. As a result, in addition to not being utilized by the building, the SDHW is impairing the efficiency of the solar thermal system; higher SDHW tank temperatures cause lower thermal transfer, which degrades solar thermal system performance. ***The percent degradation of SDHW system performance was 45% on average during the period of measurement.***[6] The correlation of morning solar preheat tank temperature to percent system performance degradation are shown in the figure below.[7]

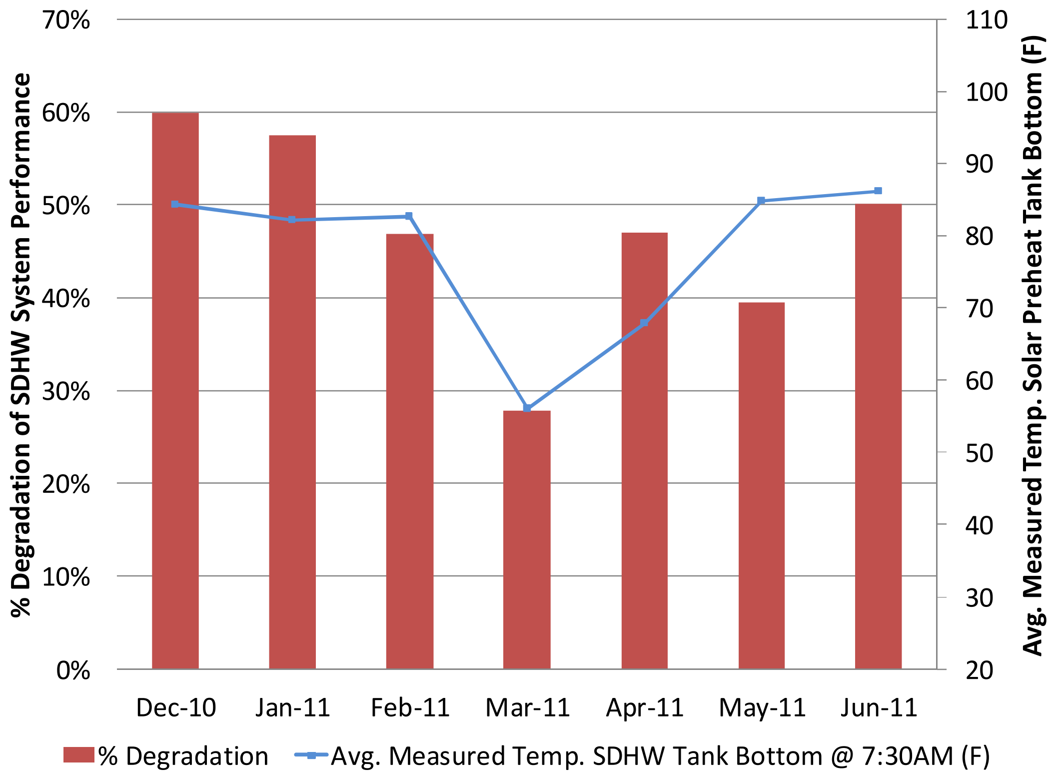

Figure S-2: Monthly average morning tank temperature and monthly total percent system degradation

Rogue bypass presents a compelling question: how could so much water be circumventing the domestic hot water system? With temperature and flow sensors on site taking readings every minute, we measured the flow rate of water entering the SDHW system; using the principles of conservation of mass and energy, we calculated rogue bypass flow and total DHW usage every minute for a three day period in March and then sorted the data from lowest

[6] Percent degradation of SDHW system performance is defined as the percent difference between modeled and measured energy production. Hourly energy simulations were completed using TRNSYS software. Measured energy production is taken from the Heliodyne Delta T Pro controller output.

[7] The correlation is imperfect in part because the % degradation is based on both measured and simulated performance. Simulated performance is based on “Typical Meterological Year” weather data, but measured performance and temperatures are dependent on the weather during the measurement period. Hence because measured and simulated data are shown on the same graph we would expect an imperfect correlation.

DHW usage to highest DHW usage[8]. The data clearly show that rogue bypass flow satisfies all of the usage below a threshold of 6 GPM. Once flow exceeds that threshold, then water begins to flow through the conventional cold water inlet to the domestic hot water system. Remarkably, rogue bypass manages to account for 82% of total DHW usage even though rogue bypass flow never exceeds 10 gallons per minute (GPM). This effect is shown in the below figure.

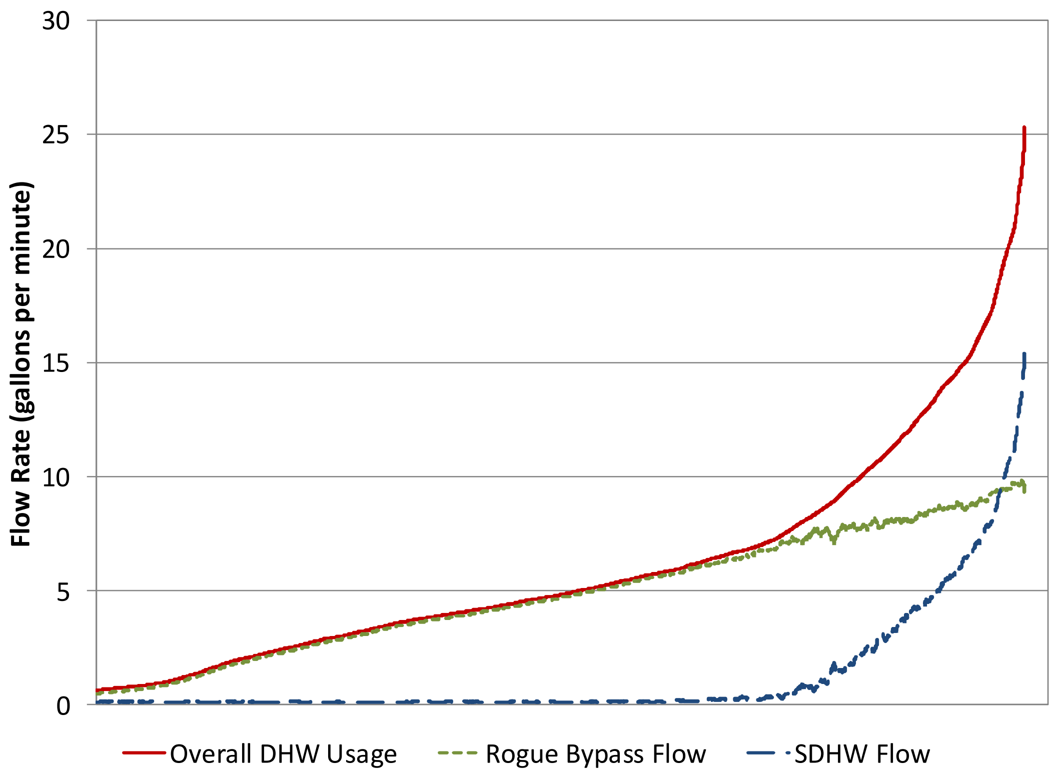

Figure S-3: Rogue bypass flow, SDHW flow, and overall DHW usage, sorted from lowest to highest usage[8]

We believe that rogue bypass is caused by cold water entering the DHW system elsewhere in the building via **crossover flow** from the cold water line to the hot water line. **Crossover flow** is recognized in the plumbing community as the unintentional flow of water between the hot and cold water lines in a building, typically via faulty check valves or mixing valves, single-spout faucets or showers, dishwashers, washing machine hook-ups, and tenant modifications undetected by building management[9]. Because crossover flow is enhanced by pressure differences

---

[8] A 30 point moving average was applied to smooth the data. The raw data is shown in an Appendix.

[9] Heschong Mahone Group, June 23, 2006. "Measure Information Template – Central Hot Water Distribution Systems in Multifamily Buildings." 2008 California Building Energy Efficiency Standards.

between the DHW and cold water lines, the numerous multifamily and commercial buildings that utilize a DHW recirculation pump are particularly susceptible.

If crossover flow is the cause of rogue bypass, how many points of crossover would be required to reach the magnitude seen in this building? A conservative estimate of crossover flow is 2 GPM per fixture[14]. Therefore, it is likely that a maximum of 5 fixtures with crossover flow are needed to reach the10 GPM of rogue bypass flow seen in this building. A detailed survey of hot water temperatures at 75% of the over 300 fixtures in the building was conducted with the hope of pinpointing the source(s) of rogue bypass flow. Some problem fixtures were located and repaired, and more than 5 additional fixtures have been identified but not yet inspected. To date, corrections have not resulted in a significant reduction of rogue bypass flow, and it remains to be seen whether the problem can be eliminated by servicing the remaining fixtures. Further work to locate and repair the exact source of crossover flow is ongoing.

The proliferation of solar thermal and other preheat systems like cogeneration requires the formulation of a methodology for diagnosing the presence of rogue bypass and the development of design changes to minimize its impact. This study presents a series of tests used to identify the presence of rogue bypass and determine the degree to which it reduces the performance of a SDHW system. Initial analysis indicates that it may be possible to diagnose the existence of rogue bypass with two temperature sensors and one pump status sensor – a fairly simple apparatus to deploy prior to solar thermal installation. This methodology should be honed by researching additional buildings so it can become a bona fide method for contractors and consultants to evaluate buildings for rogue bypass before preheat systems are installed.

While this report uncovers rogue bypass as an effect that can drastically reduce system performance for this building, further research is needed to establish the prevalence of rogue bypass in other buildings and over a longer period of time. With the simple conditions (conceivably one mis-plumbed faucet) under which rogue bypass can occur, there is a strong possibility that it is widespread. ***Given the ubiquity of DHW systems with recirculation pumps in larger multifamily and commercial buildings, including thousands of buildings in New York City and State, it is believed that rogue bypass may be an endemic problem with many solar domestic hot water and cogeneration systems, as well as other heat recovery processes. This presents a significant risk to system owners as well as utility and government incentive programs that depend on the energy savings of these systems: further research on additional buildings is highly recommended so that rogue bypass can be better understood and mitigation strategies can be more fully developed***. Specifically, we recommend studying buildings both with and without preheat systems as follows:

1. Instrumenting 20 or more buildings with a simpler 3 point monitoring system to establish a more easily deployable methodology for diagnosing crossover flow and the potential for rogue bypass.

2. Instrumenting 10 or more buildings with suspected crossover flow with the 10-point temperature and 2-point flow sensor setup used in our initial study to collect detailed data on the internal dynamics of the system.
3. Collecting data under multiple design conditions and pump operation schedules to investigate the correlation between recirculation pumping rates and magnitude of crossover flow.
4. Analyzing data to quantify the crossover flow and its impact on water, energy, and operation costs.
5. In buildings with solar thermal or cogeneration systems, verifying the existence of rogue bypass or mixing valve bypass and quantifying its impact on system performance.
6. Presenting methodology for identifying and verifying the existence of crossover flow.
7. Developing and testing the means to prevent crossover flow and rogue bypass and to mitigate their impacts to water and energy efficiency.

1. BACKGROUND

Bright Power designed and installed a 24 collector solar thermal domestic hot water (SDHW) system in a Bronx multifamily apartment building in March 2009. This system was designed following ASHRAE Solar Design Manual recommendations, as shown in Figure 1. Solar collectors were arranged in four sub-arrays of six collectors and plumbed to a boiler room to be integrated with the building's domestic hot water (DHW) system and continuously monitored with a Heliodyne Delta T Pro Controller.

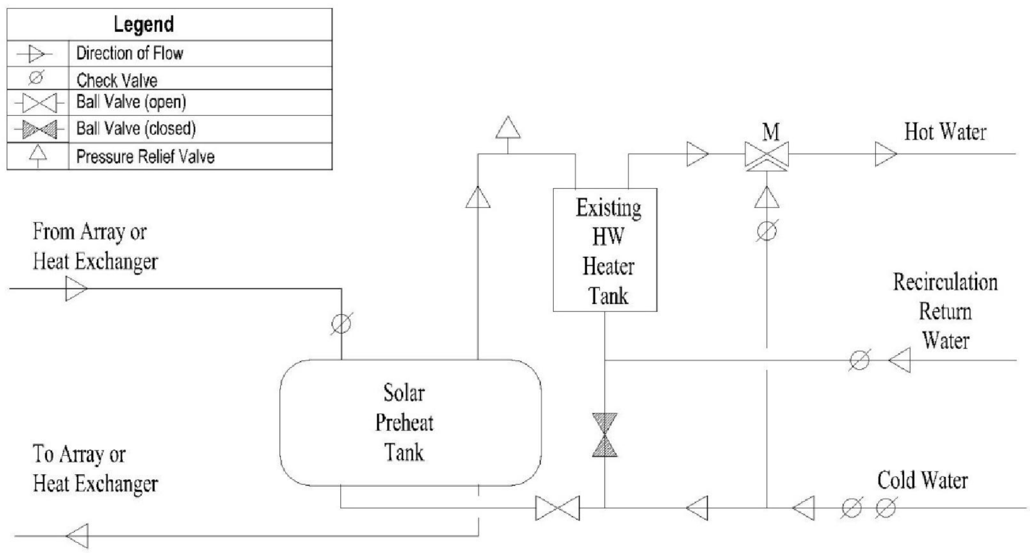

Figure 1: ASHRAE recommended system design for building with domestic hot water recirculation.[10,11].

Since its installation the system has been demonstrably underperforming. If the system were performing efficiently, all of the hot water collected in the solar preheat tank would be drawn out throughout the day and distributed to the DHW system. At night when the system is no longer collecting thermal energy, the last of the hot water would be drawn out and replaced by water from cold mains, leaving the tanks cold. Data from temperature probes installed on the preheat tank revealed that the tank temperatures remain high, and do not drop as much as expected during the night, indicating that not all of the thermal energy is being used.

Prior to this research, Bright Power conducted a number of in-house studies in an effort to determine the cause for this reduced efficiency without success. The following steps were taken to verify that the system is installed and programmed to perform as designed:

---

[10] The manual has two recommended designs for solar preheat systems interconnecting with buildings with DHW recirculation. This system is a version of the "Solar Hot Water System Interface without Solar Assist to Building Recirculation" diagram with one difference: the recirculation return line is connected to the cold side of the mixing valve. Due to the low projected solar fraction of this system, the "Solar Hot Water System Interface with Solar Assist to Building Recirculation" was not chosen.

[11] Source: Active Solar Heating Systems Design Manual. American Society of Heating Refrigerating, and Air-Conditioning Engineers. Atlanta, GA. 1988.

- Temperature probes were installed across the solar collector and heat transfer portion of the system to analyze the mass and energy flow over time
- Proper operation of the glycol side of the system was confirmed
- A specified check-valve was found to be missing and subsequently installed
- Aquastat and monitoring system setpoints were adjusted and fine-tuned
- Numerous site visits and discussions with on-site personnel and product manufacturers were conducted to verify proper design implementation

Having verified the proper design and installation of the SDHW system and monitoring equipment, it was determined that a more thorough analysis was warranted to understand the complex interactions contributing to this problem. A study was commissioned through a joint effort between Bright Power, the New York State Energy Research and Development Authority (NYSERDA), and the New York City Economic Development Corporation (NYCEDC) to investigate the performance of the system through a remote monitoring system. The existing SDHW system was instrumented with temperature, flow, and current transducer sensors and monitored over time under a variety of operating conditions.

At the outset, it was recognized that cold water bypassing the solar preheat tanks was negatively affecting the system. Our initial hypothesis was that it was solely due to water entering the DHW system via the cold side of the mixing valve, a process we termed mixing valve bypass. However, initial experiments identified another more dominant means of circumvention, which we termed rogue bypass. Further experimentation indicates that rogue bypass may be due to crossover flow in other parts of the building; cold water enters the DHW by crossing from the cold water line to the hot water line through mis-plumbed fixtures or faulty check valves, and bypasses the solar preheat tanks via the recirculation line. A theory was arrived at to explain the sub-optimal performance of the SDHW system.

A theory was developed proposing that cold water bypass is the source of system underperformance and has two components: **mixing valve bypass** and **rogue bypass**. **Mixing valve bypass**, whereby cold water enters the DHW system at the cold side of the mixing valve rather than through the solar preheat tanks, is intentional to the original design as a safety feature for summer months when the system is delivering higher temperature water than is safe for occupants. **Rogue bypass** is a phenomenon in which cold water bypasses a preheat system by entering the DHW system elsewhere in the building in a way that was not intended and difficult to pinpoint. An active recirculation pump is a necessary condition for the existence of rogue bypass.

The theory states that cold water bypass prevents SDHW from entering the DHW storage tank. Therefore, the heat produced by the solar thermal system builds up in the solar preheat tank – enough so that solar preheat tank temperatures remain high even in the morning, after most of the evening and morning occupant usage, but before the solar thermal system has turned on for the day. This compounds the performance degradation, as higher SDHW tank temperatures cause lower thermal transfer, which degrades solar thermal system performance.

The effect of the recirculation pump flow rate upon the magnitude of rogue bypass is also investigated in this study. An interesting area for further research would be on whether the pressure imbalances created by oversized a recirculation pump are sufficient in the absence of rogue bypass to degrade system performance. The effects of recirculation pump pressure are identified as an area for future research.

2. EXPERIMENTAL SETUP

In addition to the sensors installed on the solar collector and heat transfer portion of the system prior to this study, temperature, flow, and current transducer sensors were installed on the boiler room piping of the domestic hot water side of the SDHW system. This experimental setup was developed through consultation with several staff internal to Bright Power as well as Thermal Energy System Specialists (TESS), the developer of TRNSYS software, who was a consultant on this study. Specifically, TESS verified that positioning the sensors shown in the diagram below and monitoring the system at a logging interval of one minute would be sufficient to calibrate the TRNSYS model.

A schematic of the system with sensor locations is shown in Figure 2.

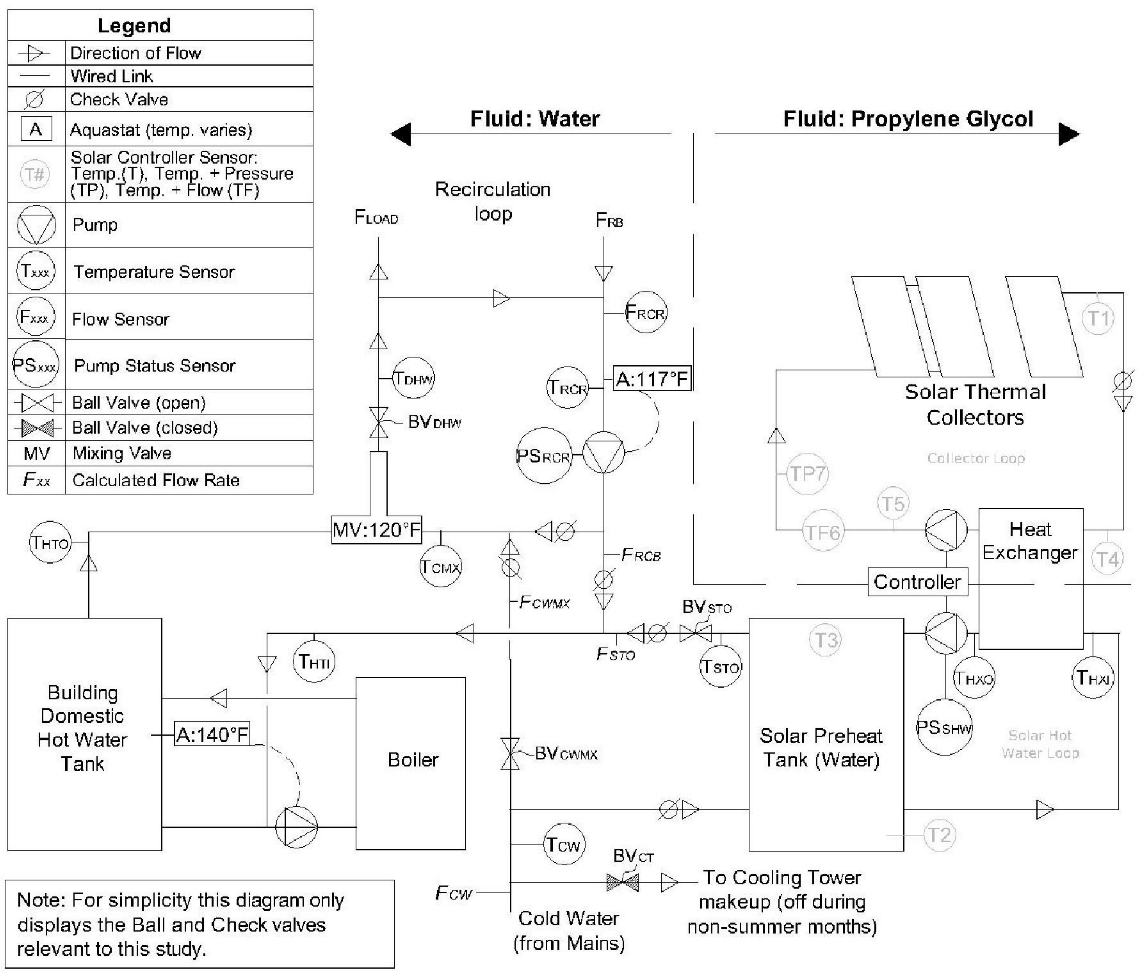

Figure 2: Schematic of solar system with sensor locations

2.1 SENSOR INSTALLATION, CALIBRATION, AND DATA COLLECTION

Descriptions of the purpose of each sensor on the SDHW system is provided in Table 1 and Table 2.

Sensor	Location	Description
T_{CMX}	Cold Side of Mixing Valve	Cold water that is mixed with water from the DHW tank to reduce the DHW to a safe level for consumption.
T_{RCR}	Recirculation Return	Water returning from the recirculation loop. It should be slightly colder than the building DHW, since the water loses heat through the piping of the entire building before returning to the DHW tank.
T_{STO}	Solar Tank Output	Outgoing water from the solar domestic hot water tank to the DHW system. This is the temperature that the solar system can heat the water without assistance from other sources.
T_{CW}	Cold Mains	Incoming cold water to the system from cold mains within the boiler room. This is the initial temperature of the water that must be heated to eventually reach the DHW out temperature.
T_{DHW}	Domestic Hot Water Output	Outgoing hot water temperature supplied to the building.
T_{HTO}	Domestic Hot Water Tank Output	By obtaining the temperatures on either side of the domestic hot water tank and solar tank external heat exchanger, the heat transfer to the two tanks can be independently calculated.
T_{HTI}	Domestic Hot Water Tank Input	
T_{HXI}	Solar Water Loop Heat Exchanger Input	
T_{HXO}	Solar Water Loop Heat Exchanger Output	
T_{BR}	Boiler Room	Ambient temperature of boiler room. Heat can build up in the room when the boilers are running.
PS_{RCR}	Recirculation Loop Pump Status	Indicates whether or not the recirculation pump is running.
PS_{SHW}	Solar Water Loop Pump Status	Indicates whether or not the pump on the solar water loop is running.
F_{CWMX}	Recirculation Return Flow Rate	Flow rate of water returning from the recirculation loop. Indicates rate at which DHW is circulated to the building.
F_{CW}	Cold Mains Flow Rate	Flow rate of incoming water from cold main entering the DHW system in the boiler room.
F_{CWMX}	Cold Water Mains to Mixing Valve	Flow rate of cold mains water to cold side of the mixing valve; also known as **mixing valve bypass**.
F_{RB}	Rogue Bypass Flow Rate	Flow rate of cold water entering the DHW system elsewhere in the building; also known as **rogue bypass.**

Table 1: Water Circulation Loop Sensors (via HOBO U30 datalogger)

Sensor	Location	Description
T1	Solar Panel Output	Temperature of glycol at the outlet from the solar panel
T2	Bottom of Preheat Tank	Temperature at the outlet from the solar domestic preheat tank returning to the heat exchanger.
T3	Top of Preheat Tank	Temperature of water at the inlet to the solar domestic preheat tank.
T4	Heat Exchanger Inlet	Temperature of glycol at inlet to heat exchanger
T5	Heat Exchanger Outlet	Temperature of glycol at outlet from heat exchanger
TF6	Heat Exchanger Outlet	Flow rate of glycol at outlet from heat exchanger
TP7	Heat Exchanger Outlet	Pressure of glycol at outlet from heat exchanger

Table 2: Solar collector loop sensors (via solar thermal controller datalogger)

The ten 12-Bit Onset temperature sensors were attached directly against the exposed pipe beneath the existing insulation to ensure minimal contact with the air in the room. A small amount of thermal heat transfer grease was applied to the sensors before placement to facilitate heat transfer. Before installation the temperature sensors were calibrated with one another relative to hot and cold temperature sinks. The sensors were determined to be in good and working order when all sensors read within ±0.5°F of each other.

Flow rates at two locations were continuously monitored using an external ultrasonic flow meter: 1) at the cold mains input in the boiler room and 2) at the recirculation return inlet to the mixing valve. The flow meter used was the GE AquaTrans AT868 Panametrics Liquid Flow Ultrasonic Transmitter (GE Measurement and Control Solutions 2010), which consists of a central unit with two sets of clamp-on transducers. The flow transducers were installed according to the product instructions on areas of cleaned, bare pipe with 10 pipe-diameters of straight pipe upstream and 5 pipe-diameters of straight pipe downstream.

The flow sensors, though calibrated independently by a lab, were also field calibrated on site; flow was induced across a length of pipe on which the sensors had been installed by draining water from the DHW storage tank into a bucket of known volume and comparing the flow meter readings to the flow rate measured manually. After a satisfactory phase of testing and monitoring they were determined to be capable of providing sufficiently accurate readings. Data from the calibration process are included in the appendix to this report.

The sensor data were output to a HOBO U30 datalogger at a logging interval of one minute, with each data point representing the average of six individual readings over the course of the logging interval in order to achieve more accurate data collection, as no “spikes” in usage were missed. This level of resolution was specified by TESS to be adequate to accurately calibrate the TRYNSYS model.

Onset HOBO current transducer sensors were installed on the recirculation pump and the solar hot water pump and used to monitor the current flowing through the pump circuits in order to determine when the pumps operate.

3. OBSERVATIONS AND THEORY

3.1 SYSTEM UNDERPERFORMANCE

The solar thermal system in this study was designed to displace 11-12% of the energy required to supply the building's domestic hot water.[12] If the hypothesis of cold water bypass is correct, we should expect to see a substantial impact to the amount of energy supplied by the solar thermal system. The correlation of morning solar preheat tank temperature and percent system performance degradation are shown in the figure below -- the percent degradation of SDHW system performance was 45%, on average.

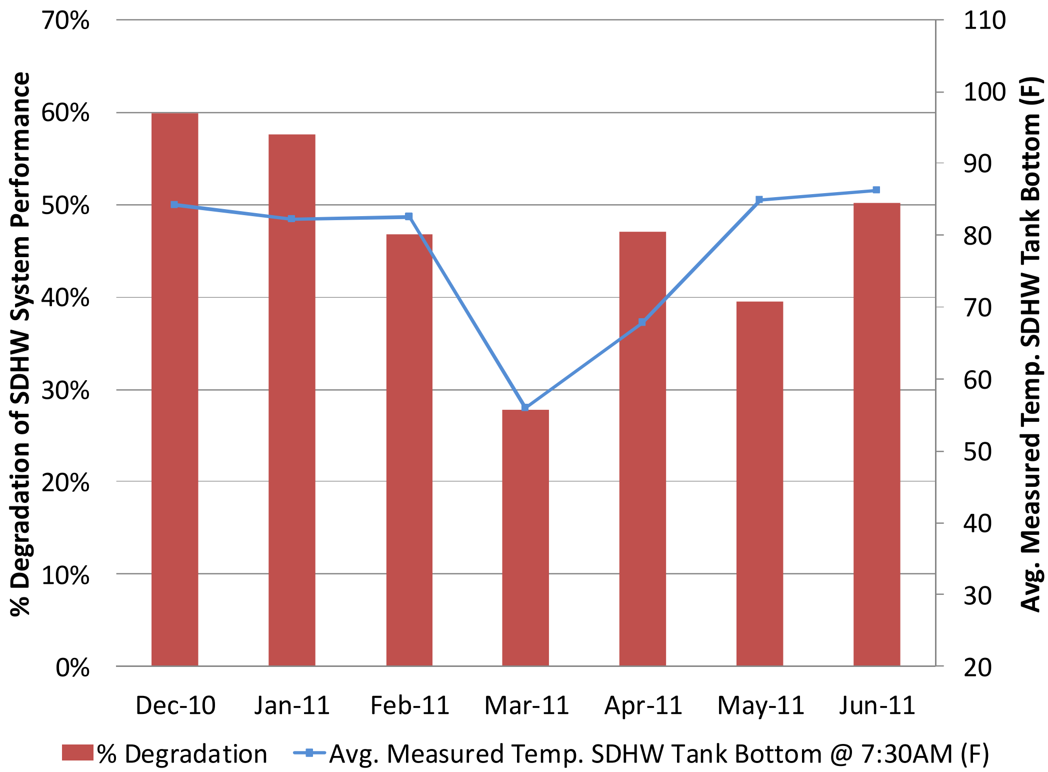

Figure 3: Negative impact to system performance correlated with reduced flow through solar preheat tanks

[12] RET Screen v3 predicted a solar fraction of 13.2% with no shading. With the shading at the site, we estimate the solar fraction to be 11-12%.

3.2 COLD WATER BYPASSING THE SOLAR THERMAL SYSTEM

Part 1 of the initial hypothesis was that the system is underperforming in part due to mixing valve bypass; cold water bypass occurring at the cold side of the mixing valve. When the ball valve BV_{CWMX} (see Figure 2) is open, the cold side of the mixing valve is supplied by both cold mains water and recirculation return, and cold water flows directly to the mixing valve rather than passing through the solar preheat tank. This theory was confirmed through experimental analysis (see Section 4.3). However, when ball valve BV_{CWMX} was closed, cold water bypass remained present; further analysis revealed that the total flow rate of cold water entering the boiler room was consistently one-quarter to one-fifth of expected levels for a building with 315 occupants. We theorize the missing source of water is "rogue bypass" as defined earlier. Subsequent experiments were performed to verify the existence of rogue bypass, quantify its impact, and attempt to locate its source. These experiments are described in Section 4. A theoretical discussion of rogue bypass is presented in the Section 3.3.

3.3 THEORETICAL MODEL OF ROGUE BYPASS

The amount of crossover flow contributing to rogue bypass can be theoretically quantified through a mass and energy balance. The following methodology can be applied to any DHW system with a recirculation pump.

Consider the point on Figure 2 at which the rogue bypass flow enters the system (e.g. a mis-plumbed faucet). At that point we apply the concepts of conservation of mass and energy. These simply state that mass or energy cannot be created nor destroyed. Flow rates are simply a measure of mass delivered over time, so at this point:

$$F_{RCR} = F_{RCR}' + F_{RB} \tag{1}$$

Where F_{RCR} is the recirculation flow downstream of this point, F_{RCR}' is the recirculation flow upstream of this point and F_{RB} is the additional flow added to the recirculation loop at this point. The flows into and out of the point must be equal for conservation of mass.

By a similar argument conservation of energy requires that the energy flow into and out of this point must be equal. The amount of energy contained in water is determined by its specific heat capacity (mcΔT) and is proportional to flow multiplied by temperature. Thus:

$$T_{RCR}F_{RCR} = T_{RCR}'\,F_{RCR}' + T_{CW}F_{RB} \tag{2}$$

Where T_{RCR}' is the temperature of the recirculation flow upstream of rogue bypass, T_{RCR} is the measured temperature of the return line, and T_{CW} is the measured temperature of the cold water mains.

By rearranging equation (1) to isolate F_{RCR}' we get:

$$F'_{RCR} = F_{RCR} - F_{RB} \tag{3}$$

Which we can substitute into equation (2) and rearrange for F_{RB} :

$$F_{RB} = F_{RCR}\frac{(T_{RCR} - T_{RCR}{}')}{(T_{CW} - T_{RCR})} \tag{4}$$

$F_{RCR,}$ T_{RCR} and T_{CW} are measured values while $T_{RCR}{}'$ can be determined by considering what the return line temperature would be in the absence of rogue bypass. Radiative losses in the recirculation loop mean that even with no cold water added to the loop the returning water arrives cooler than is was sent to the building. During periods of no draw, no cold water is added to the loop and so the radiative losses can be estimated by:

$$\Delta T_{loss} = \min(T_{DHW} - T_{RCR}) \tag{5}$$

This can then be used to estimate the upstream recirculation temperature in equation (4):

$$T_{RCR}{}' \approx T_{DHW} - \Delta T_{loss} \tag{6}$$

With our measurements of $F_{RCR,}$ T_{RCR} and T_{CW} we can now calculate the predicted rogue bypass flow (F_{RB}). See Section 4.6.

3.4 PRESSURE DIFFERENCES CAUSED BY THE RECIRCULATION PUMP

Part 2 of the initial hypothesis was that over-pressurization of the recirculation loop prevents the draw of water from the solar preheat tanks. After further investigation this theory was revised to address the relationship between the recirculation pump and rogue bypass. The solar pre-heat tanks are located on the 9th floor roof and are at mains pressure reduced by the head loss at this height. The possible sources of rogue bypass are all on lower floors with less head loss and consequently higher pressure. Any sources of water entering the loop at point of higher pressure will contribute more volume as a fraction compared to lower pressure sources. This means that water will preferentially enter the recirculation loop via sources of rogue bypass located below the roof, impeding the draw from the tanks. We theorize that higher pressure in the recirculation loop exacerbates this effect.

Prior research suggests that crossover flow is enhanced through interactions between the recirculation pump and low-flow fixtures; pressure imbalances at the fixture can facilitate the transfer of water from the hot to the cold side, or vice versa. For example, when a 1.5 GPM single-spout water fixture with two knobs (one hot, one cold) is opened it effectively connects the hot and cold lines, which are flowing at 3-5 GPM[13]. A Heschong-Mahone Group Study indicates that crossover flow is conservatively 2 GPM per fixture.[14]Any pressure imbalance in the system, caused, for example, by an improperly installed tempering baffle, creates the opportunity for water to transfer from the cold to the hot or vice versa. The problem would be exaggerated by large pressure imbalances created by an oversized recirculation pump; according to the Energy Design Resources' design brief on central DHW systems in multifamily buildings, an overpowered recirculation pump will increase the rate of crossover flow.[15] This theory is investigated in Section 4.7.

4. EXPERIMENTAL INVESTIGATION

As stated previously, it was observed that even though heat from the solar system is collecting in the solar preheat tanks, the water is not drawn out of the tanks at the intended rate and is therefore not being effectively distributed to the building hot water supply. It was theorized that this was due to (1) cold water bypassing the solar thermal system, and (2) over-pressurization in the recirculation loop. This theory was investigated through the following experiments.

4.1 EXPERIMENT 0: Simulated Performance Degradation

A model of the system was created using the Transient System Simulation Tool (TRNSYS) and a series of simulations were carried out in an effort to corroborate the theory that not all of the cold water entering the DHW system is drawn through the solar preheat system as designed, and that there is an appreciably adverse effect on the system's solar fraction as a result.

The first exercise is a simple analysis of the solar system operating with progressively less flow through the solar preheat tanks. The reduced flows correspond to progressively increased percentages of net cold water bypass (specifically 0, 80, 90, 95, 96, 97, 98, and 99%). Net cold water bypass is assumed to be the combined sum of mixing valve bypass and rogue bypass, the assumption being that the impact of bypass is the same irrespective of the means of circumvention. The model was used to simulate the amount of thermal energy produced in each case. Results are presented below.

---

[13] Horner, Russ, President. Water management Inc. Alexandria, VA. Personal Correspondance. May 2011.
[14] Heschong Mahone Group, June 23, 2006. "Measure Information Template – Central Hot Water Distribution Systems in Multifamily Buildings." 2008 California Building Energy Efficiency Standards.
[15] Energy Design Resources. Central DHW Systems in Multifamily Buildings California Public Utilities Commission. San Francisco, CA.. Design Brief. January 5, 2010.

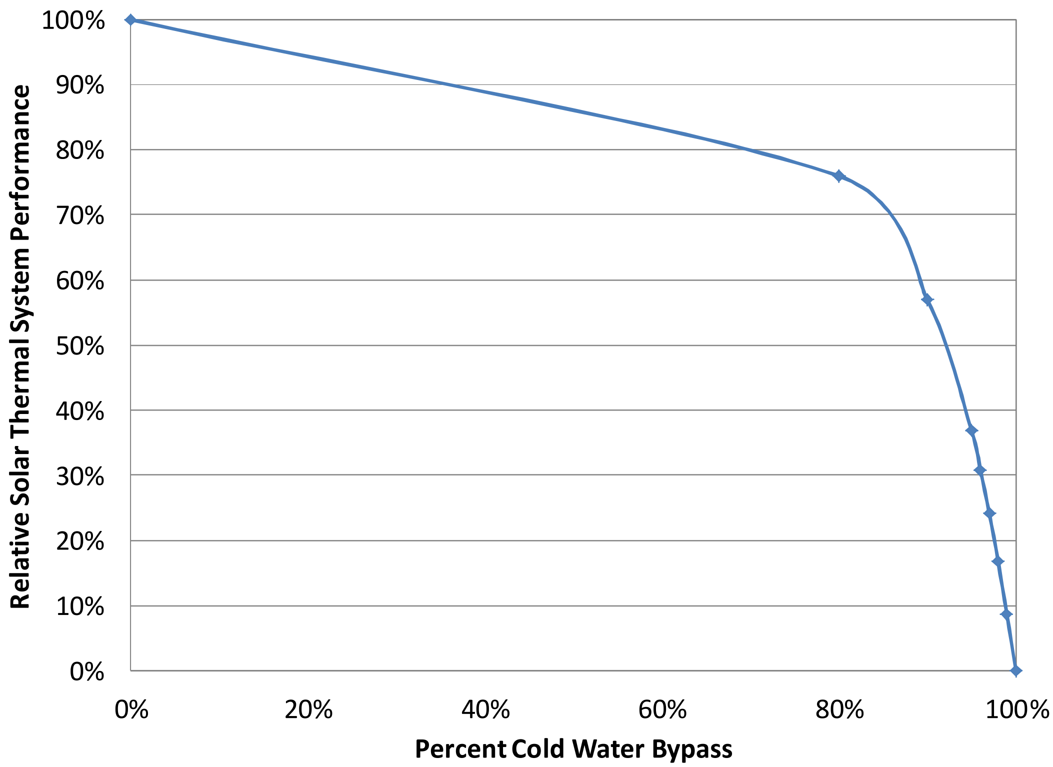

Figure 4: Simulated degradation of thermal energy production due to cold water bypass

This experiment shows that increasing cold water bypass is a driving force behind system performance degradation, regardless of whether it manifests as rogue bypass or mixing valve bypass. As described in the hypothesis, the theoretical reason behind this system performance degradation is that increasing cold water bypass results in decreasing flow through the system. A solar preheat tank with less flow through it remains warmer and therefore has less efficient heat transfer with the solar thermal system. Figure 5 displays that as cold water bypass increases, the morning average solar preheat temperature remains much warmer. 7AM is chosen as a time to represent tank temperature because it is before the solar thermal system activates, but after much of the evening and morning draw for the building has occurred.

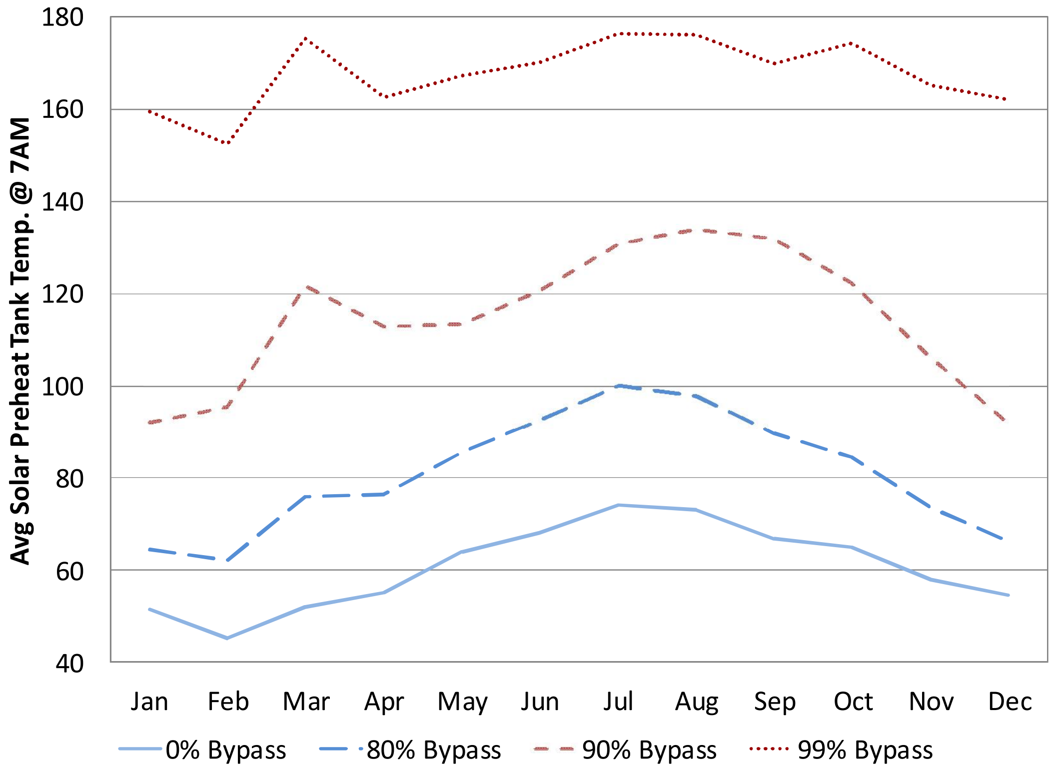

Figure 5: Simulated average solar preheat tank temperatures for increasing percentages of net cold water bypass

It is important to consider that the solar thermal system has a high limit preheat tank temperature of 180°F. In the theoretical 99% bypass case, the preheat tank temperature hovers between 155°F and 180°F at 7AM. Not only does the solar preheat tank have a lower thermal heat transfer efficiency, but the capacity of the tank to accept more energy is a limiting factor.

4.2 EXPERIMENT 1: Simulated Evidence of Rogue Bypass Flow

A second simulation exercise was performed dealing primarily with the calibration of the model vis-à-vis simulated versus measured data for a 15-day period in late April and early May 2011.[16]

Analysis of the simulated recirculation loop provided evidence in support of the existence of rogue bypass flow. The length of the recirculation loop was estimated to be 900 ft (450 ft supply, 450 ft return). It was noted that with the

[16] The results of this exercise are discussed in greater detail in the appendix of this report. An additional exercise in which a whole-system simulation of the system was attempted ; this exercise is discussed in Section 4.9.

assumed 27 GPM flow rate, a 900 ft loop, 1.5” pipe, ¾” insulation, and a 68°F ambient temperature, the modeled return temperatures were only a fraction of a degree below the supply temperatures, while the measured data had shown significantly lower return temperatures.

As the system is designed, the mixing valve has no way of mixing water stored in the DHW storage tank at 140°F down to the DHW supply temperature of 120°F unless the return temperature is considerably below the supply temperature because there is no way for cold water to enter the mixing valve from anywhere other than the recirculation-return line when BV_{CVMX} is closed.

The fact that the measured supply temperature stayed near 120°F and the system did not overheat is an indication of one of two things;

1) Cold water is entering the recirculation loop and is contributing to the drop in the return temperature, or
2) The recirculation loop thermal losses are higher than estimated.

To test the second theory, both the insulation thickness and the length of the recirculation loop were modified to increase the temperature drop across the building and artificially create a return temperature low enough for the mixing valve to maintain 120°F.

It was found that with if the insulation thickness is decreased to zero, a 2000 ft loop would be needed to keep the system from overheating. Keeping the insulation thickness at ¾” would require a 5000 ft loop. The fact that the recirculation loop would have to be so much longer and/or the insulation level would have to be nonexistent in order to achieve the thermal losses needed to recreate the measured return temperatures is strong evidence that cold water is in fact entering the system.

4.3 EXPERIMENT 2: Mixing Valve Bypass

Our initial theory hypothesized that cold water from the mains plumbing line was bypassing the solar thermal system solely via mixing valve bypass: water enters the DHW system at the cold side of the mixing valve rather than at the SDHW tank. As can be seen in Figure 2, when the ball valve BV_{CWMX} is open, the cold side of the mixing valve is supplied by either the cold water mains, or the recirculation loop. When cold mains water enters the cold side of the mixing valve, it tempers the water from the DHW storage tank before being sent to the building and then returns to the boiler room via the recirculation loop. It then travels into the building DHW storage tank to be reheated by the boiler or is sent back to the cold side of the mixing valve, skipping the solar hot water system entirely.

To investigate this theory, data were collected when the ball valve BV_{CWMX} was closed and compared to data collected with the valve open. The following figure is a plot of the difference in temperature at the top and bottom of the solar preheat tank during the course of two weeks. From June 30th to July 6th, the ball valve is closed. On July 7th at 11:30 am, the ball valve was opened and remained open through July 13th.

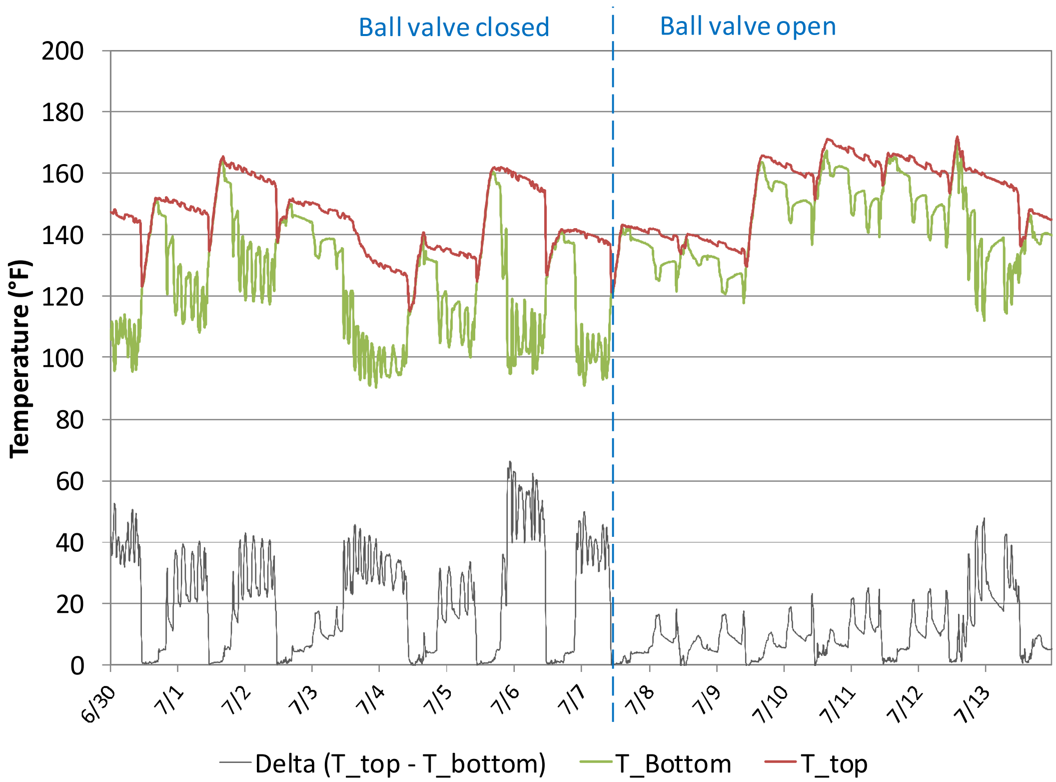

Figure 6: Temperatures at top and bottom of solar preheat tank with ball valve open (6/30 to 7/6) and closed (7/7 to 7/13)

As stated previously, if the system were performing optimally, the hot water collected in the solar preheat tank would be drawn out throughout the day, and at night when the system is no longer collecting thermal energy, the last of the hot water would be drawn out and replaced by water from cold mains, leaving the tanks cold and ready to store new energy the following day. Because the solar preheat tank is stratified in temperature, it follows that a greater temperature difference between night and day means that more of the water in the tank is emptying out and the thermal energy is more efficiently used.

Note that before July 7th, the temperature at the bottom of the tank ranges from about 95°F to 140°F, while after July 7th both top and bottom temperatures rise about 20 degrees, with the bottom tank temperature typically being between 140°F and 160°F. On average, the delta between the top and bottom of the tank when the valve was closed was 30°F overnight and 16°F during the day. After the valve was opened, the overnight delta was 13°F and the daytime delta was 9°F. This shows that the water in the tanks is turning over less frequently, and indicates that less cold water is being drawn through the solar preheat tanks than when the ball valve is open and less of the solar thermal energy stored in the tanks is being distributed to the building. This confirms the theory that when the ball valve is open, some cold water is bypassing the solar preheat tanks via mixing valve bypass, decreasing the performance of the SDHW system.

BV_{CWMX} was therefore valved off, forcing all cold water drawn from cold mains across F_{CW} to pass through the solar preheat tanks before entering the DHW system, and the system was left to run for the winter season. However, it was found that the flow patterns through the solar preheat tanks were not sufficiently altered to improve the system performance to its design efficiency. This result suggested that mixing valve bypass is not the sole source of the problem, and that cold water is entering the DHW system elsewhere in the building and bypassing the solar preheat tanks via the recirculation-return line. The initial theory was revised to include this additional rogue bypass and investigated through further experimentation.

4.4 EXPERIMENT 4: Water Usage Comparison and Draw Profile

New York City's Department of Environmental Protection (DEP) tracks daily water consumption data for individual water meters using an automated meter reading system. Daily consumption data for the month of April from the DEP database were used to calculate the estimated monthly hot water use for the building assuming that 28% of a building's water use is for hot water (70 gal/person/day total usage, 20 gal/person/day DHW usage).[17] When compared to data from the flow sensor measuring cold water entering the boiler room from cold mains (F_{CW}), it was found that the estimate of hot water based on the DEP data is dramatically higher, indicating that a significant amount of water used for DHW is entering the system through an alternate route: rogue bypass. By these calculations, in the month of April, rogue bypass accounted for an average of 72% of cold water used for DHW heating. The estimated and actual water consumptions are presented in Table 3.

[17] Residential water use as reported by NYC.gov is 60-70 gal/person.day. ASHRAE estimates for DHW use per person per day are 14 gal(low), 30 gal(med), 54 gal(high). We chose 20 gal/person/day DHW usage because this is a recent construction building so it has low flow fixtures, but not the lowest possible.

DATE	Total Usage from DEP (gal)	Estimated gal DHW (28%)	F_{CW} (gal)	% diff
04/01/2011	7921	2218	847	62%
04/02/2011	15140	4239	1546	64%
04/03/2011	15102	4229	1455	66%
04/04/2011	13210	3699	1168	68%
04/05/2011	13464	3770	1121	70%
04/06/2011	13756	3852	1308	66%
04/07/2011	12858	3600	1064	70%
04/08/2011	14212	3979	789	80%
04/09/2011	14736	4126	1452	65%
04/10/2011	15327	4291	1687	61%
04/11/2011	12581	3523	737	79%
04/12/2011	14362	4021	1179	71%
04/13/2011	13419	3757	953	75%
04/14/2011	13584	3803	1087	71%
04/15/2011	13501	3780	1034	73%
04/16/2011	14511	4063	1184	71%
04/17/2011	15461	4329	1360	69%
04/18/2011	13546	3793	808	79%
04/19/2011	13524	3787	701	81%
04/20/2011	9193	2574	1275	50%
04/21/2011	13232	3705	1010	73%
04/22/2011	12918	3617	1225	66%
04/23/2011	13464	3770	1143	70%
04/24/2011	13606	3810	1029	73%
04/25/2011	12402	3473	1206	65%
04/26/2011	13808	3866	1124	71%
04/27/2011	10322	2890	1003	65%
04/28/2011	16276	4557	1086	76%
04/29/2011	13255	3711	609	84%
04/30/2011	17541	4911	997	80%

Table 3: Comparison of total building DHW consumption to water entering the boiler room through the intended route

According to the building management, there are approximately 315 residents in the building. If all of the flow were through F_{CW} (and there were no rogue bypass flow), that would indicate only about 3.5 gallons of DHW per person per day, which is far below the typical 14 to 30 gallons per person[18]. Put simply there is not enough cold water entering the boiler room to account for all of the domestic hot water 315 people would use, or that the city claims it is delivering. This make-up water is entering the system somewhere else, which we hypothesize is rogue bypass flow entering the recirculation loop.

[18] ASHRAE 90.2-2001: Energy Efficient Design of Low-Rise Residential Buildings. Atlanta: ASHRAE publications, 2001.

4.5 EXPERIMENT 5: Establishing Existence Rogue Bypass Flow (F_{RB})

The two pairs of ultra-sonic flow transducers were installed on the F_{CW} pipe in the boiler room. With BV_{CWMX} closed this is the point at which all cold water is expected to enter the DHW system (assuming the absence of rogue bypass). Hence, flow rates measured on this pipe should correlate with the DHW draw for the building.

The flow rates measured by the flow meter at this point were compared to a quantified draw induced by progressively opening hot water taps of measured flow-rate elsewhere in the building. The results are shown in Figure 7. The induced flow rates were found to be 2 to 4 GPM higher than the flow rates measured through F_{CW} in the boiler room, with the discrepancy widening as the induced flow increased. It is therefore theorized that during this test, 2 to 4 GPM of the demand was satisfied by water contributed by crossover before a draw on F_{CW} was activated. This contribution from crossover is the quantity of water bypassing the solar preheat tanks via rogue bypass.

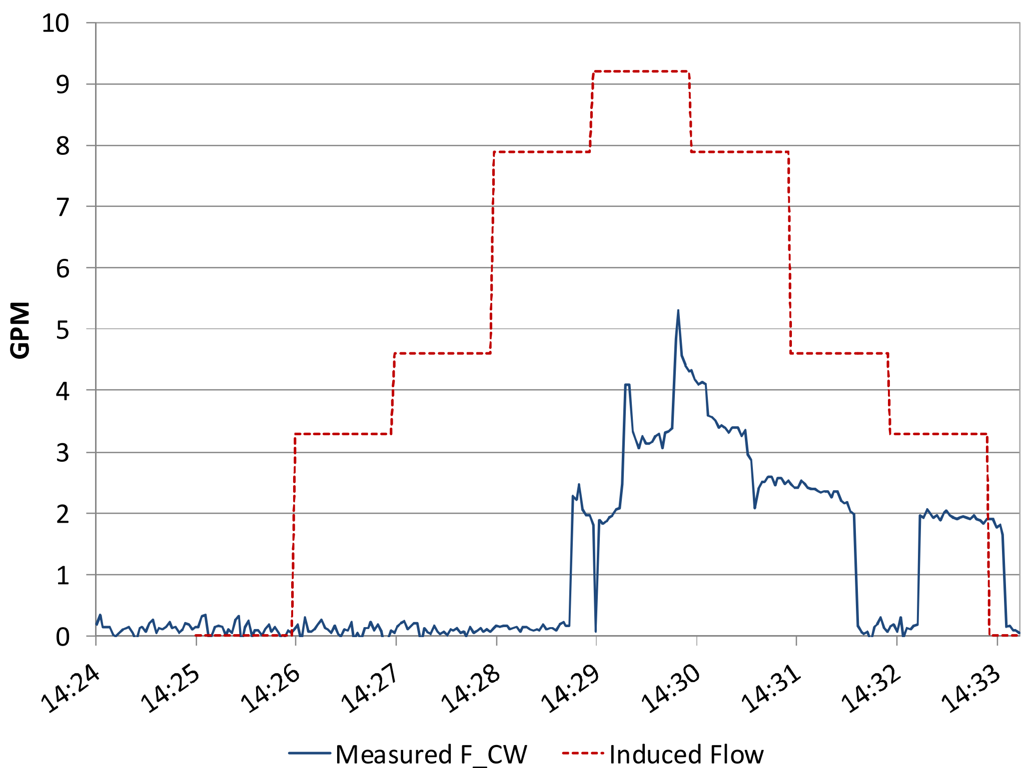

Figure 7: Comparison of measured vs. induced flow rates in the absence of mixing valve bypass

We see in this figure that – measured induced flow in the building is significantly greater than measured flow entering the domestic hot water system via the cold mains inlet to the system through F_{CW}. This would be impossible to explain without the existence of another source of cold water to the domestic hot water system.

4.6 EXPERIMENT 6: Energy Balance Using Instrumented Data)

The percent rogue bypass was calculated on a weekly basis by performing an energy balance as described previously in Section 3.3 using instrumented data collected during the monitoring period. It was found that on average, rogue bypass is contributing 82% of the cold water entering the DHW system. A thermodynamic analysis of the DHW system during the same period confirmed that the SDHW system was underperforming significantly (see figure below)[19], with the underperformance greatest when rogue bypass is highest.

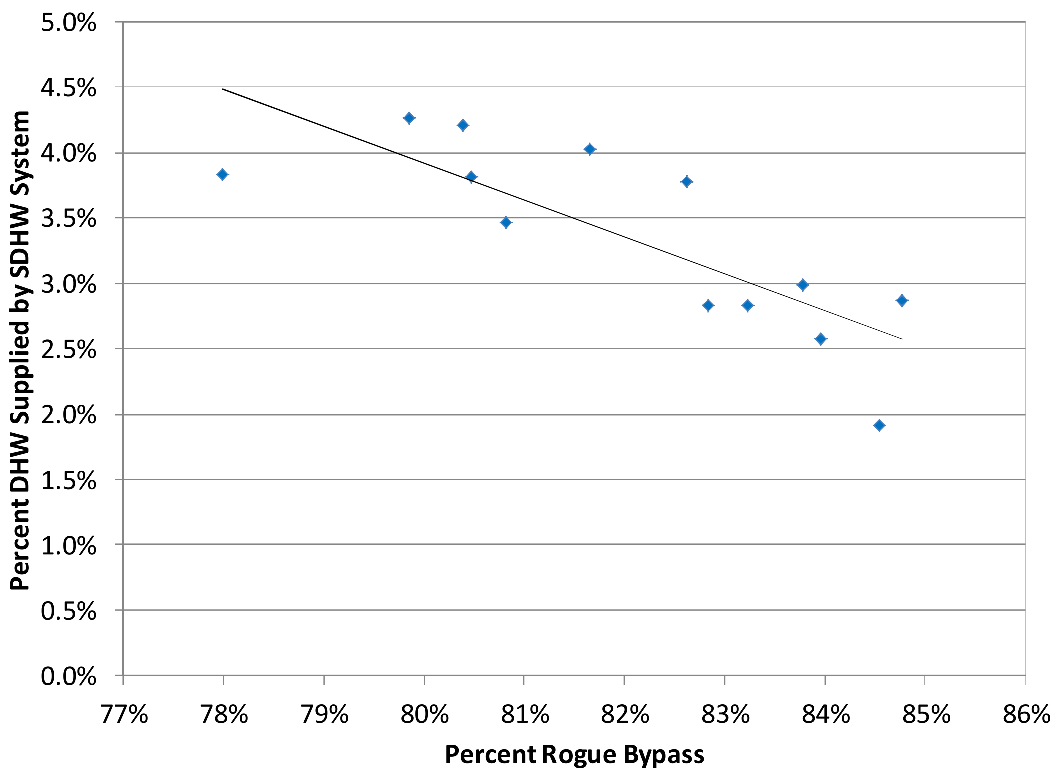

Figure 8: Correlation between weekly averages of % rogue bypass % DHW supplied by the SDHW system (by volume)

While rogue bypass flow is fairly consistent day to day, the minute by minute fluctuations are more striking, as can be seen in the daily data plotted below.

[19] The ball valve BV_{CWMX} was closed during the time that these data were collected, meaning that all cold water bypass is occurring through rogue bypass.

The negative impact of rogue bypass on solar thermal system performance is clear, but the reason behind it is not immediately apparent until more granular data is viewed. The below figure presents the usage profile for a typical day, together with the rogue bypass and cold water mains flow rate.

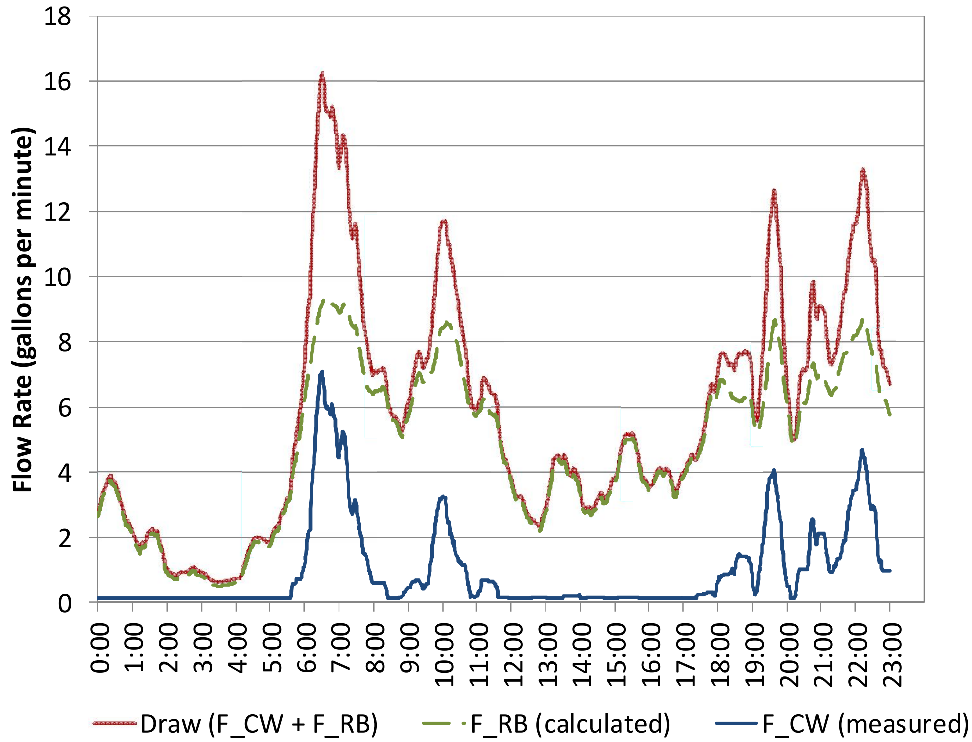

Figure 9: Typical daily profile of DHW usage, rogue bypass flow (F_RB), and solar preheat tank flow (F_CW)

It is clear that rogue bypass (F_{RB}) satisfies all of the load below a certain threshold. F_{CW} only supplies any significant portion of the load when the overall demand for hot water increases beyond a certain level. This leaves large periods of the day where no water flows through F_{CW} at all. This helps to explain why our T_{CW} temperature sensor often read temperatures well above what would be reasonable if fresh cold water were flowing through those pipes. To understand the exact point of threshold below which rogue bypass supplies all usage water, it is useful to sort the minute resolution data from lowest usage to highest usage as presented in the figure below.

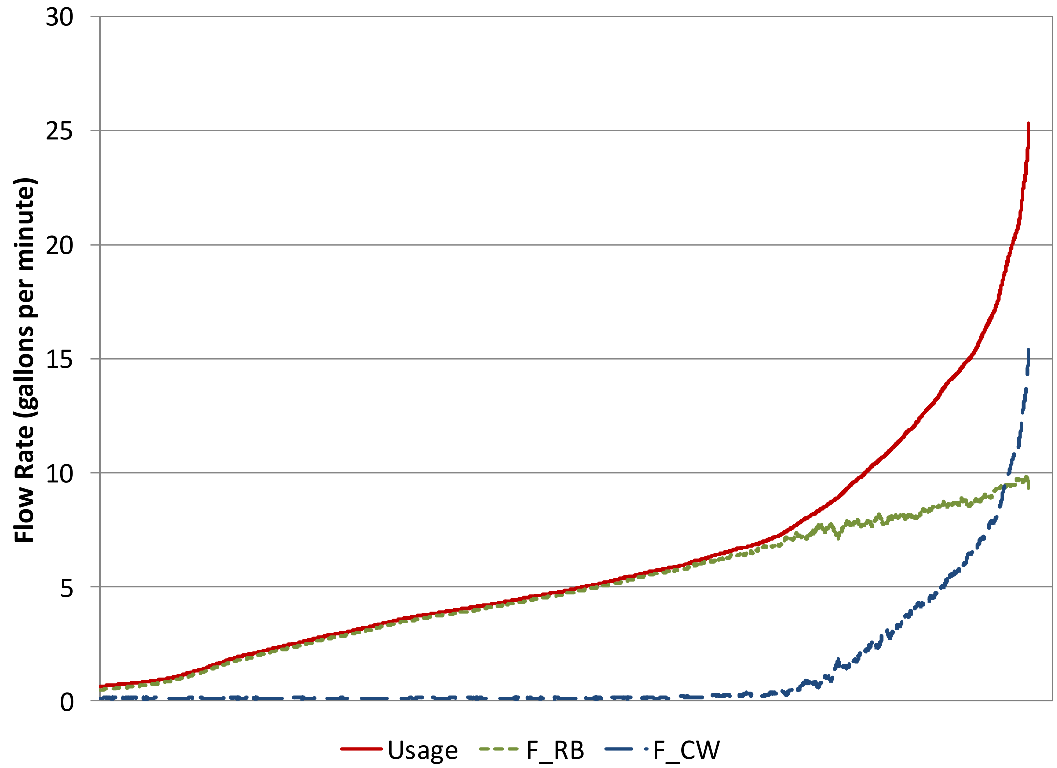

Figure 10: One minute measurements of DHW usage, rogue bypass flow (F_RB), and solar preheat tank flow (F_CW), sorted from lowest usage to highest usage[20].

It is apparent from the above figure that rogue bypass flow accounts for the first 6 – 7 GPM of flow into the DHW system. Beyond that threshold, an increasing percentage of the domestic hot water is supplied by flow through the solar preheat tank (F_{CW}), but rogue bypass continues to increase linearly. Also, rogue bypass is greater than solar preheat tank flow in almost all instances; only under rare circumstances does F_{CW} exceed F_{RB}. This helps to explain why rogue bypass is meeting 82% of the demand: because it meets a certain base threshold and the building demand is below that threshold most of the time.

4.7 EXPERIMENT 7: Over-Pressurization in Recirculation Loop

To corroborate the correlation between recirculation pumping rate and crossover flow discussed in Section 3.4, data were collected from the building during periods when two different sized recirculation pumps were in operation. Both pumps operated constantly during their respective time periods.

Prior to February 28th, 2011, the DHW system at the host site was installed with a 3/4 HP recirculation pump, which was larger than necessary for the building's DHW demand. On February 28th, the pump was replaced with a 1/3 HP

[20] A 30 data point moving average was also applied to smooth the data. The unaltered graph is visible in the appendix

pump. This change reduced the average flow through the DHW system (F_{CWMX}) from about 39 GPM to about 27 GPM.

The mass and energy balance described previously was used to analyze the flow characteristics before and after this change[21]. The results were used to quantify the change in rogue bypass flow and verify that the recirculation pumping rate impacts the amount of cold water entering the DHW system via crossover flow. The following table presenting weekly averages before and after the pump change shows that the average percentage of rogue bypass drops from 93% to 82%[22].

Week	% RB	% SDHW
February 17-23	92%	1.6%
February 24-27	94%	1.1%
March 1-5	80%	4.3%
March 6-12	78%	3.8%
March 13-19	80%	4.2%
March 20-26	82%	4.0%
March 27-April 2	80%	3.8%
April 3-9	83%	2.8%
April 10-16	83%	2.8%
April 17-23	84%	2.6%
April 24-30	84%	3.0%
May 1-7	85%	2.9%
May 8-14	83%	3.8%
May 15-21	85%	1.9%
May 22-28	81%	3.5%

Table 4: Weekly averages of rogue bypass flow and DHW supplied by SDHW system before and after downsizing of recirculation pump

4.8 EXPERIMENT 8: Temperature Survey – Location of Crossover Flow Causing Rogue Bypass

The Heschong Mahone Group has found that crossover flow can occur through a missing or defective check valve on the cold water supply, through single-spout faucets or showersin apartments, or through portable dishwashers and clothes washers or other tenant modifications unrecognized by building management.

In an effort to identify the source of the crossover flow causing rogue bypass at the host site, a survey of hot water temperatures was conducted throughout the building with the hope of isolating the potential source to a specific riser or risers, anticipating that the temperature would be lower along a riser in which cold water is crossing over into the DHW line.

[21] Note that ball valve BV_{CWMX} was closed for the duration of this experiment.

[22] Unfortunately, data from before February 17th is not available because the monitoring system was not yet in place and operational.

The following schematic illustrates the typical plumbing configuration in a multi-family building with a recirculation loop. Hot water from the DHW tank is distributed to apartment fixtures through a series of risers, all of which connect to the recirculation loop which cycles the water back up to the boiler room. Plumbing plans indicate that this building is plumbed with 20 risers.

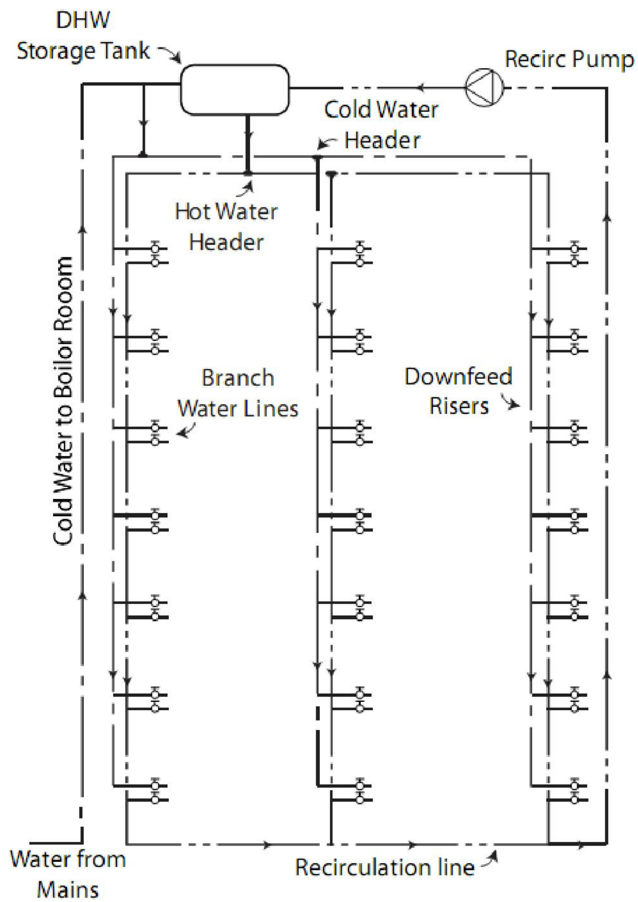

Figure 11: Example schematic of riser and recirculation loop configuration

Data collected during times of low draw when rogue bypass is at minimum indicate that the typical heat loss across the building is only 1-3°F. If crossover flow occurs at any of the fixtures on a given riser, it follows that the temperature of the hot water at that fixture and at fixtures further down the riser will measure appreciably lower than the temperature of the water leaving the DHW tank. Potential sources of crossover flow can therefore be located by comparing the temperatures measured at the fixtures to the temperature leaving the boiler room (T_{DHW}) at the time of measurement.

The survey was conducted in three stages:

Stage 1: In the first stage, 25 fixtures were surveyed and the following observations were made:

1. The temperatures at all but one faucet ranged between 117.5°F and 123°F, which is consistent with what was expected based on the temperature of the DHW leaving the boiler room.
2. The temperature at the bathtub faucet in one apartment was measured at 112°F at 2:34 pm on May 6, 2011, at which time the temperature of the water leaving the boiler room was 119°F.
3. The kitchen faucet in one apartment was found to be defective: when the hot water was turned on partway, water was delivered at about 120°F, but when the faucet was turned on all the way the water stopped completely and the faucet behaved as if it were off.

The two anomalous faucets were investigated as possible sources of crossover flow and replaced with new fixtures that corrected the problem. However, a subsequent mass and energy balance showed no demonstrable impact to the percent of rogue bypass flow calculated to be entering the DHW system, indicating the presence of additional sources of incursion.

Stage 2: In the second stage of the survey, a temperature probe was installed at the inlet to the building's laundry facility, and set to log temperatures at an interval of one minute for the period of a week. At the end of the week the data were analyzed for anomalous deviations in temperature, but the data reflected a draw profile consistent with normal operation. This indicates that the source of rogue bypass flow is not associated with the laundry facility.

Stage 3: The third stage of the investigation involved a more comprehensive survey of the building in which the temperatures at 75% of the building fixtures were recorded along with the date and time of observation. Architectural and plumbing plans were used to associate each fixture in the building with its plumbing riser, and the data were analyzed in an attempt to locate potential locations for crossover as sources of rogue bypass flow.

Fixtures with temperatures greater than 115°F were considered normal, while fixtures with temperatures below 110°F were considered likely sources of rogue bypass and flagged for further inspection. Fixtures with temperatures between 110°F and 115°F were considered irregular and were also recommended for follow-up investigation.

Of the twenty plumbing risers identified, three were found to service a majority of the fixtures with lower than expected temperatures; P3, P11, and P11A. A schematic showing the results of the temperature survey and the path of these three risers is provided below. This diagram labels floor numbers on the left vertical axis and apartment labels (A, B, C, etc.) within each box.

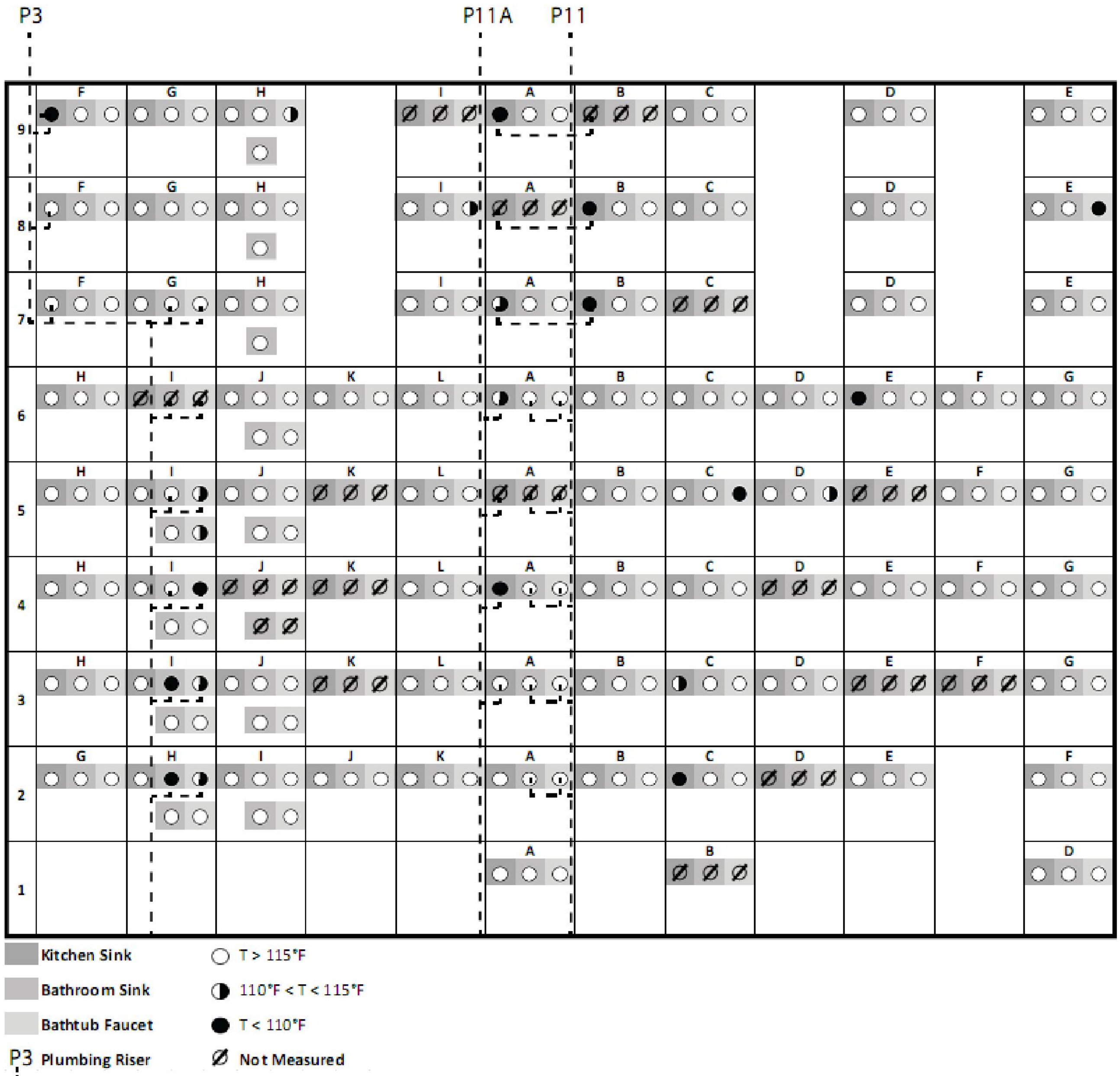

Figure 12: Schematic of results of a temperature survey of building fixtures with possible sources of rogue bypass identified

Several of the other lines with fewer irregular features may have shown more definitive evidence of crossover, but a pattern could not be established since a number of the fixtures along these lines could not be measured due to difficulties in accessing the apartment. For example, line P15 (not shown in Figure 12) does not have any irregular fixtures, but eight of the 17 fixtures along that line were not observed. Likewise, line P8 has only one irregular fixture, but ten of its 24 fixtures were not measured. Furthermore, some of the lines may have opportunities for crossover that were not immediately apparent based on the plumbing plans available. For example, P13 and P13A share a sanitary riser and several other utility lines, and between the two of them there are three irregular fixtures and four fixtures that were not measured.

The results of this investigation were shared with the building management with the recommendation to inspect all fixtures and accessible pipe fittings along these lines for proper installation and operation with particular emphasis given to lines P3, P11, and P11A. Follow-up research will include an analysis of any notable information reported from these inspections.

4.9 EXPERIMENT 9: Whole-System Simulation

A model of the entire DHW system (solar preheat, DHW boiler heat, and recirculation loop) was created in an attempt to more accurately assess the impact of cold water bypass on the SDHW system's performance, as quantified by the annual solar fraction. The goal of this exercise was to estimate the benefit of diagnosing the presence of rogue bypass and implementing design solution to mitigate the effects of cold water bypass in general.

Significant problems were encountered in implementing the simulation. Repeated attempts to calculate the solar fraction for a range of combinations of % rogue bypass and % mixing valve bypass consistently produced unrealistic results. After repeated analysis, we determined that part of the problem lies in the modeling of the mixing valve which can constantly adjust to incoming temperatures and the fact that TRNSYS cannot take pressure into account in its simulations; the complicated dynamics at this point involve too many unknown variables to formulate a unique solution without an additional physical relationship. Furthermore, based on the model's behavior, we were unable to establish a methodology for calculating the solar fraction; the simulations produced output temperatures of T_{DHW} that fluctuated and dropped below the 120°F setpoint. While this is consistent with our instrumented data, it made it impossible to calculate the solar fraction in the standard way, which is predicated on a constant output temperature. Eventually it was determined that the dynamics of the system are far more complex than could possibly be modeled with TRNSYS given time and budget constraints associated with this project.

5. CONCLUSIONS

5.1 SYSTEM UNDERPERFORMANCE

The following conclusions on SDHW system's reduced performance can be drawn from the investigation presented in this report:

- Cold water bypass demonstrably impairs the performance of the solar domestic hot water system by diverting flow around the solar preheat tanks.
- There are at least two pathways of cold water bypass: mixing valve bypass, and rogue bypass.
- Rogue bypass is the dominant bypass effect, whereby 82% of the cold water entering the DHW system does not go through the preheat tanks. This accounts for a reduction in system performance by 45%, on average.
- In the presence of rogue bypass, the system performance is further degraded by mixing valve bypass, whereby water bypassing the solar pre-heat tanks in the boiler room via the cold side of mixing valve reduces the flow of water through solar preheat tanks.
- Oversized recirculation pumps and associated higher flow rates inthe recirculation loop exacerbate cold water bypass.
- Further research would be needed to carry through the TRNSYS model through the full system simulation. Because we were not able to create a calibrated energy model capable of simulating the full system, we cannot account for all the factors responsible for decreased system efficiency. The other experiments performed demonstrate that performance is affected by cold water bypass significantly, and by over-pressurization in the recirculation loop to a lesser extent.

5.2 RECOMMENDATIONS AND FURTHER RESEARCH

There are significant benefits to formalizing a methodology for diagnosing the presence of crossover flow and developing techniques to mitigate its impact, particularly when crossover results in rogue bypass as this is one of its most serious effects.

Formalize a Diagnostic Methodology

The following is a preliminary list of potential strategies to identify crossover and establish its impact to building systems and the potential for rogue bypass. These are listed from easiest to most difficult:

- Monitor and compare the temperatures of the DHW sent to the building and the temperatures of the water coming back in the recirculation-return line. In a properly functioning system the heat load of the building will remain relatively constant and the temperature drop between these two points will fluctuate minimally.

If rogue bypass is present, however, the intermittent influx of cold water will make the delta between these two temperatures much more erratic.

- Install flow sensors on the DHW and RCR lines and monitor them during periods on zero draw. If the flow in the recirculation return line remains close to the flow in the DHW line during periods of high draw, this is evidence of crossover flow.
- Solicit tenant feedback and note instances of significant anomalies; significant variations in DHW temperature, hot water in the toilets, having to wait excessively long for water to get hot.
- Turn off the hot water supply valve to a selection of fixtures in the building one at a time focusing on those identified by tenants as problems fixtures. While it is off, turn on the hot water faucet at that fixture and wait several minutes. If any cold water comes out, this could be a source of crossover flow and rogue bypass. Repeat with cold water supply valve.[23]

Test and Disseminate Proposed Solutions

Crossover prevention

- Avoid installing single-spout faucets and shower mixing valves
- Require backflow prevention valves on hot and cold water lines between problem fixtures and the preceding tee
- Install properly sized recirculation pumps and consider installing demand or temperature modulation controls on the recirculation system to minimize pump operation. Energy Design Resources' design brief of central DHW systems in multifamily buildings recommends flow rates between 1.5 and 3.5 feet per second. These flow rates are low enough to minimize pressure imbalances and high enough to prevent debris settlement in the pipes.[24]

Problem mitigation

- For solar thermal systems, install a temperature controlled 3-way diverting valve to divert the recirculation water to the solar preheat tank or to the DHW tank depending on the solar preheat tank temperature. This will force the recirculation return water through the preheat tank when the temperature of the tank is hotter than the recirculation return water[25]. A similar approach can be used for a cogeneration system.

---

[23] Central DHW Systems in Multifamily Buildings California Public Utilities Commission. Design brief. San Francisco: Energy Design Resources, 2010.
[24] Central DHW Systems in Multifamily Buildings California Public Utilities Commission. Design brief. San Francisco: Energy Design Resources, 2010.

[25] Source: Active Solar Heating Systems Design Manual. American Society of Heating Refrigerating, and Air-Conditioning Engineers. Atlanta, GA. 1988.

- To mitigate mixing valve bypass, install a temperature controlled 3-way diverting valve to divert either solar preheated water (when it is cool enough) or cold mains water (when solar preheat is too hot) to the cold side of the mixing valve for tempering.
- Conduct an extensive survey of all fixtures in the building, measuring the temperature at each tap and closing off the hot and cold valves as described in the fourth bullet point in the diagnostic methodology described above. Fix any defective fixtures and re-perform the diagnostic tests to determine if the problem has been corrected.

Further Research

Future research would aim to establish the frequency of the problem and quantify its impacts in buildings (1) without preheat processes associated with the DHW system and (2) with solar thermal or cogeneration systems vulnerable to rogue bypass. A preliminary investigation strategy would include:

- Instrumenting 20 or more buildings with a pump-status sensor on the recirculation pump and temperature probes on the DHW and recirculation-return lines to diagnose the existence of crossover flow. In a properly functioning system the temperature difference between the DHW sent to the building and the water in the recirculation-return line should vary smoothly according to pump operation and outdoor temperature, whereas if crossover flow is present it will also vary based on usage.
- Instrumenting 10 or more buildings with suspected crossover flow with the 10-point temperature and 2-point flow sensor setup used in our initial study to collect detailed data on the internal dynamics of the system.
- Collecting data under multiple design conditions and pump operation schedules to investigate the correlation between recirculation pumping rates and magnitude of crossover flow.
- Analyzing data to quantify the crossover flow and its impact on water, energy, and operation costs.
- In buildings with solar thermal or cogeneration systems, verifying the existence of rogue bypass or mixing **valve bypass** and quantifying its impact on system performance.
- Presenting methodology for identifying and verifying the existence of crossover flow.
- Developing and testing the means to prevent crossover flow and rogue bypass and to mitigate their impacts to water and energy efficiency.

6. APPENDIX

6.1 IMPLICATIONS OF CROSSOVER FLOW

Our findings lead us to believe that the effect of rogue bypass on the dynamics of the building's plumbing system could potentially have much broader implications. In this building the preheat tanks were supplied by a solar thermal system, but the effects studied in this project could equally well affect cogeneration systems or other heat recovery processes used in domestic hot water heating.

Rogue bypass is one of many effects of the larger under-investigated problem of crossover flow – the unintentional flow of water between the hot and cold water lines in a building. The implications of crossover flow include the following:

Rogue Bypass and Underperformance of Solar Domestic Hot Water and Cogeneration Systems:

- The impact to solar thermal and cogeneration systems are examples of crossover flow causing rogue bypass, whereby cold water bypasses a preheat circuit that is critical to the operation of the system.
- This results in increased demand on conventional DHW systems to compensate for SDHW or cogeneration underperformance.

Overuse of recirculation pump:

- Colder water in the recirculation-return line causes the recirculation pump to run more frequently, increasing the energy needed to run the pump.
- This results in unnecessary wear and tear to pumping equipment and wasted electricity.
- The need for higher pumping rates can lead to the installation of over-sized recirculation pumps, which results in more wasted electricity.

Inconsistent DHW temperatures:

- DHW temperatures can vary by as much as 40°F within a single multifamily apartment building when cold water crosses into the hot water line via crossover flow.
- To satisfy the DHW needs of all tenants, building management often raises the set-points on the DHW boiler and recirculation pump to excessively high levels.
- Overheated DHW represents a substantial safety hazard and wasted energy.

Reduced appliance efficiency and tenant satisfaction:

- Low flow fixtures do not demonstrate the water and energy savings expected because of the increased time required to run the water to reach an appropriate temperature.

- Appliances such as dishwashers that raise water temperatures to suitable temperatures via electric resistance must expend extra energy to reheat water cooled by crossover flow.

6.2 DAILY AVERAGED FLOW PROFILES

The averaged results of this energy balance performed over a twelve day period[26] are presented in **Error! Reference source not found.** and compared to the building's average DHW usage (draw) and the average flow through F_{CW}(the amount of cold water entering the DHW system through the boiler room.

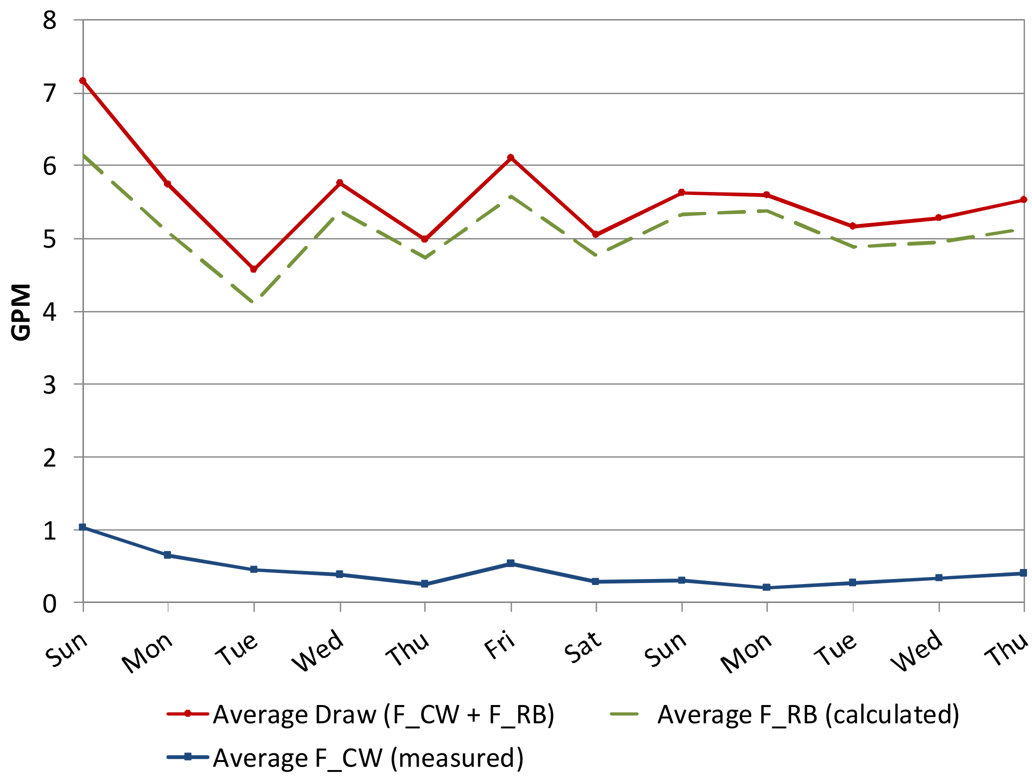

Figure A-1: Averaged daily flow rates

6.3 FLOW METER CALIBRATION

6.4 TRNSYS ENERGY MODEL REPORT

---

[26] February 16-27

7. REFERENCES

ASHRAE 90.2-2001: Energy Efficient Design of Low-Rise Residential Buildings. American society of Heating Refrigerating, and Air-Conditioning Engineers. Atlanta, GA. 2001.

ASHRAE Solar Design Manual. American society of Heating Refrigerating, and Air-Conditioning Engineers. Atlanta, GA. 1988.

Central DHW Systems in Multifamily Buildings California Public Utilities Commission. Design brief. San Francisco: Energy Design Resources, 2010.

Horner, Russ, President. Water management Inc. Alexandria, VA. Personal Correspondance. May 2011.

"Residential Water Use." *NYC Department of Environmental Protection*. Web. 01 Aug. 2011. <http://www.nyc.gov/html/dep/html/residents/wateruse.shtml>.